(Preprint) AAS 19-093

# THE DEEP SPACE POSITIONING SYSTEM (DPS) – NAVIGATOR CONCEPT FOR THE LUNAR GATEWAY

Joseph R. Guinn*, Shyam Bhaskaran*, Todd A. Ely*, Brian M. Kennedy*, Tomas J. Martin-Mur*, Ryan S. Park*, Joseph E. Riedel*, Duane C. Roth*, Andrew T. Vaughan*

The DPS-navigator concept is a self-contained autonomous navigation hardware and software system that provides spacecraft on-board navigation throughout the solar system. It works like the Global Positioning System (GPS), but without the need for the satellite infrastructure. For the lunar Gateway, DPS-navigator observes lunar landmarks to determine position information and computes orbital maneuvers to maintain the Gateway orbit when the crew is not present or to reduce the crew's dependence on ground-based mission control. The optical only design is small (25 x 12 x 12 cm) and light weight, less than 5 kg. Power requirements are less than 12 W with self-contained processing. Data link requirements (infrequent for set-up, monitoring, and maintenance) are less than 50 MB per day. DPS-navigator leverages prior flight demonstrations of autonomous navigation (DS-1, Deep Impact, Stardust) to provide a more general and robust on-board solution. DPS-navigator provides precise lunar landmark measurements using narrow angle field of view (FOV) optics and precise pointing knowledge using wide angle FOV optics. A more robust configuration of the DPS-navigator uses optical and radiometric sensing. For the lunar Gateway, the optical only version is sufficient given the abundance of optical targets in the form of lunar surface landmarks. On-board navigation performance results using lunar landmarks are presented in this paper and shown to provide an alternative to traditional deep space network Earth-based radiometric techniques; thus, freeing Earth tracking stations and ground personnel for other support.

## INTRODUCTION

Beyond near-Earth and the reach of Global Navigation Satellite Systems (GNSS), spacecraft navigation relies on traditional Earth-based techniques. Radiometric and/or optical measurements from special ground-based observatories can be used to guide spacecraft to the far reaches of the solar system. Fully autonomous navigation systems are primarily desired to enable collection of science observations where long light-time delays with Earth cannot be tolerated. High speed small body flybys or impacts are examples of scenarios that benefit the most from autonomous navigation. Increasingly, eliminating the reliance on limited or compromised Earth-based tracking resources also drives the need.

* Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

To date, a single deep space autonomous navigation system has been demonstrated, the same one on three different missions. This system, "AutoNav," used optical data of the approach target.[1,2,3,4] Radiometric data provides excellent geocentric navigation, but for any target other than Earth, Moon and Mars, *in situ* target-relative navigation will be required for precise targeting (such as landing). Short of planting radio beacons on the targets of interest, optical navigation must be used in such cases. To provide the ability to return a spacecraft safely to Earth without a ground link (e.g., during periods of compromised telecommunications) optical measurements and trajectory change maneuvers must be processed on-board autonomously.

DPS-Navigator is a self-contained "box" that consists of the sensors, computer and flight software that leverage the "AutoNav" experience. It uses self-pointing narrow and wide-angle cameras to take images of near-field objects (distant asteroids, or a planetary target) and background stars to determine the position of the camera (and therefore the host spacecraft). These processed data, reduced to precise inertial angle measurements, could be passed to a resident GN&C system, or processed within DPS-Navigator itself, to provide prime or back-up position determination. The determination of spacecraft position and velocity is via a least-squares estimate using dynamical models of the spacecraft motion through the solar system with all gravitational and non-gravitational perturbations accurately accounted for. With the estimate of the position and velocity in hand, trajectory correction maneuvers can be computed.

Optical Navigation (OpNav) is an ideal way to provide automated and autonomous navigation for deep space exploration to bodies whose positions are not well known. Missions to bodies other than the Moon or Mars, that demand very precise positioning relative to the surface of that body (e.g. 10's of meters), will require *in situ* target relative navigation. In the case of a spacecraft returning to Earth, though the position of the Earth in heliocentric space is very well determined (to the meter level), without an Earth-radio-link it may be impossible to accurately determine the position of the Earth (e.g., to the level of a few km) due to the uncertainty of the position of the Earth's limb as seen through the atmosphere. For this, alternative means of relative navigation may be necessary, such as optically observing artificial satellites, or even the Moon itself, such a capability is possible with DPS-Navigator.

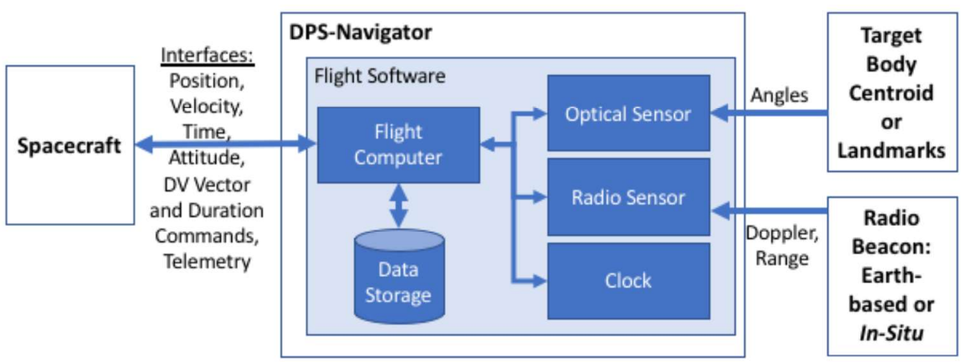



**Figure 1. DPS-Navigator**

Though OpNav is the core capability for *in situ* observations of the target, DPS-Navigator would also feature an option to provide powerful 1-way Doppler radiometric measurements from a known-source beacon, which could be an Earth station or another spacecraft. Software within the Iris radio[5] extracts these observables and provides them to the DPS-Navigator orbit determination filter. For the highest accuracy radiometric data, a very stable frequency reference is necessary, which could be provided by the Deep Space Atomic Clock (DSAC) that is being developed by STMD. The DSAC conditions the frequency reference being used to drive the transmitter within the Iris radio. In combination (Figure 1), the 1-way radiometric and optical data of the DPS-Navigator provide a robust navigation solution for virtually any deep space navigational challenge.

Exploration spacecraft like Orion, require automated safe return. The Orion project currently has a requirement to provide for automatic safe return of the crew and spacecraft to Earth in an emergency, and especially in the event that the radio-link is compromised to the point of making Earth-based radiometric navigation impossible.[6] In this event, without a backup capability, loss of crew or loss of mission is highly possible if not probable. For this serious contingency, DPS-Navigator could serve as a remediation, by providing optical measurements to the resident GN&C system.

DPS-Navigator integrates several flight-proven or flight-inheritance technologies: the miniature MRO OpNav telescope[7], the Iris radio (which flew to Mars on the MARCO cubesat missions), motor-actuators and rate control (as will fly on OCO-3 and has flown on GRAIL), the Mars2020 EECam CMOS 20Megapixel camera electronics and detectors, the Deep Impact AutoNav autonomous navigation flight software system (with additional Stardust and Deep Space 1 flight heritage), the MER X-band patch antenna (for the 1-way radio link navigation), and a command and control s/w suite that has been the automated robotic control language used on over a dozen of NASA's missions, including the Spitzer space telescope and Mars Reconnaissance Orbiter.[8,9]

The overall operation of DPS-Navigator is very analogous to the manner of operation of a star tracker providing automated spacecraft attitude. Though planned as an instrument that could be replicated for multi-use on a variety of NASA's missions (as well as commercial missions), the system can be adapted to a number of configurations. Where self-pointing cameras cannot be accommodated, due to mass or other constraints, the AutoNav software aboard the IRIS software-defined-radio (SDR) could accommodate images from a small fixed camera, making the DPS-Navigator system compatible even for use on a CubeSat. But for crewed and larger robotic missions the capabilities of the full DPS-Navigator instrument provides the greatest cost to benefit ratio.

In addition, the instrument could serve as a powerful sensor to detect internal structure, strength and motion of dynamic and energetic bodies such as Europa, Io, and Enceladus.[10,11,12,13] The genesis of the DPS-Navigator instrument is the Advanced Pointing and Imaging Camera (APIC) that has completed risk-reduction engineering work under SMD's Homesteader program. Figure 2. shows the dual optical sensors designed to obtain very high-resolution images of planetary surfaces while simultaneously determining the pointing from the camera to that surface. This enables extraction of information related to motions and deformations in planetary surfaces. The requirements to obtain this very precise geometric information are exactly the same as those required for high-precision optical navigation; thus, the DPS-Navigator/APIC instrument could perform both functions. In 2014, DPS-Navigator was awarded a US patent for the various options and configurations in which DPS-Navigator can be instantiated.[14]

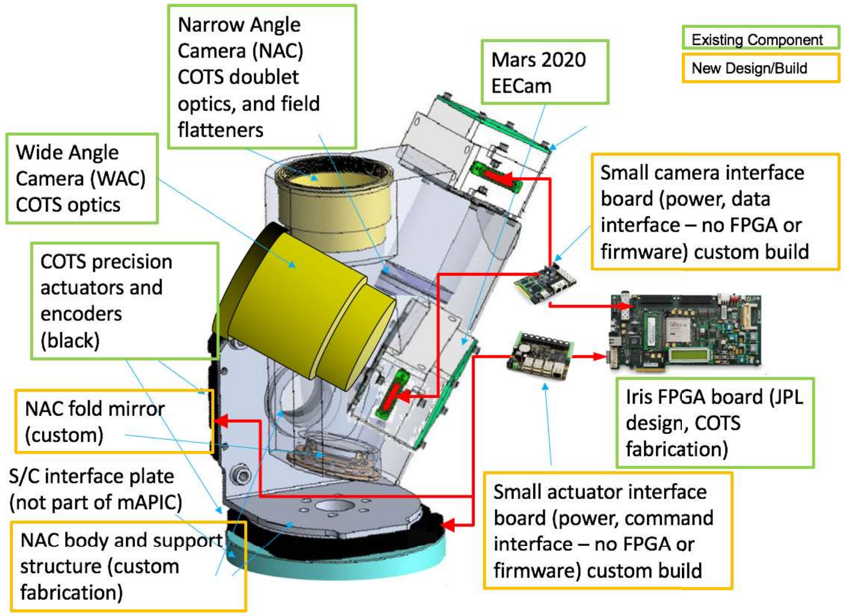



**Figure 2. Optical Sensors of DPS-Navigator**

## NAVIGATION PERFORMANCE AT THE LUNAR GATEWAY

The proposed lunar Gateway near the Moon is planned as a staging point for renewed lunar exploration and eventual deep space crewed missions. To support these plans, the Gateway is intended to serve as a proving ground for deep space technologies like the DPS-Navigator.

The current Gateway orbit is a cislunar Near Rectilinear Halo Orbit (NRHO).[15,16] The baseline NRHO is a southern halo in a 9:2 resonance with the lunar synodic period. The orbit passes through perilune over the north lunar pole approximately every 6.5 days with a close approach radius of about 3,200 km and an apolune radius of approximately 70,000 km. While the target NRHO exhibits its nearly stable characteristics, an uncontrolled spacecraft in the NRHO will eventually depart the vicinity of the Moon. Small orbit maintenance maneuvers (OMMs) are required to ensure long-term operations in the NRHO, and the cost of the OMM depends on the quality of the orbit determination solution available. Solar pressure and the gravity gradient near perilune affect the spacecraft attitude, and moments can be significant, especially on long Gateway stacks. An appropriately sized attitude control system is needed to maintain spacecraft attitude. The frequency of attitude control activity significantly drives orbit determination accuracy.

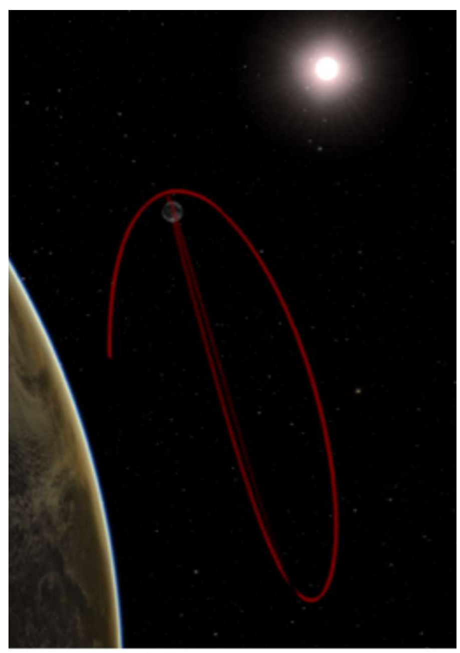


**Figure 3. DSG Orbit View from Earth**

A Power and Propulsion Element (PPE) is envisioned to be the first and primary module of the Gateway. It would also provide communications and navigation tracking services. While the PPE has low-thrust propulsion capabilities, chemical propulsion maneuvers are required for OMMs. The PPE would be the preferred element to host DPS-Navigator; however, any future element with sufficient PPE communications interfaces could host DPS-Navigator.

The principal navigation challenge in cislunar space is to continuously maintain knowledge of the orbital position and velocity to enable design and execution of OMMs. Modelling of gravitational and non-gravitational perturbations are refined using Earth-based radiometric tracking from NASA's Deep Space Network (DSN). Orbit determination performance using the DSN suggests at least three contacts per week, each 6-hours long, are needed to meet the velocity knowledge requirements.[17] This paper extends that analyses to show the performance using on-board optical measurements only.

**Ground-Based Orbit Determination Performance**

Ground-based orbit determination uncertainties were assessed by conducting a linear covariance analysis. Varying amounts of DSN radiometric tracking measurements were assumed. Since the DSN stations are globally distributed (Madrid/Spain, Canberra/Australia, Goldstone/USA), near-continuous tracking is possible. While this is beneficial during crewed operations, it is desirable to understand the minimal tracking needs - especially during uncrewed periods.

The DSN measurements used in this study were S-band, two-way Doppler and range. Simulated DSN ground station observations were constrained to be no longer than six-hours and to be above 10 deg elevation. Doppler measurements were assumed to be averaged over 60 seconds with 1 mm/s (1σ) random noise. Range measurements were simulated with 1 m (1σ) random noise and were accumulated over five-minute intervals. Key dynamical error sources affecting the orbit determination knowledge included: attitude control via Control Moment Gyro (CMG) or Reaction Wheel (RW) desaturations, imperfect maneuver executions and venting due to crew related activities. Assumptions for the size and frequency of these error sources are shown in Table 1.

**Table 1 – Orbit Determination Error Assumptions**

| Error Source | Model Parameters | Error : Frequency | Reference |
|---|---|---|---|
| Gravity: Point Mass | Earth, Sun & Jupiter | none | JPL DE430 |
| Gravity: Central Body Oblateness[11] | Lunar degree and order 8x8 | none | GRAIL: GL900C |
| Solar Radiation Pressure | PPE Solar panels: $200 m^2$ x 2, PPE Bus: 5m diameter | 10 % (1σ) : constant bias | |
| Attitude Control: CMG/RW Desaturations | PPE thrusting (chemical) | 0.5, 1.0, 2.0 cm/s (1σ) all axes : once per orbit at ~20° before apolune | |
| Orbit Maintenance Maneuvers | PPE thrusting (chemical) | 2 cm/s (1σ) all axes : once per orbit at apolune | |
| Venting: Pressure Swing Adsorption[18] | Stochastic acceleration, Uncorrelated Process Noise: $4 \times 10^{-9}$ $ft^2/sec^3$ | $7.7 \times 10^{-10}$ $km/sec^2$ (1σ) : Every 623.9 sec | MPCV Technical Brief, FltDyn-CEV-16-50 |
| Venting: Waste Water Dumps[18] | Stochastic acceleration, Uncorrelated Process Noise: $1 \times 10^{-9}$ $ft^2/sec^3$ | $1.0 \times 10^{-10}$ $km/sec^2$ (1σ) : Every 3 hours | MPCV Technical Brief, FltDyn-CEV-16-50 |

| | | | |
|---|---|---|---|
| DSN Radiometeric Tracking | S-Band Doppler | 1.0 m (1σ) : Every 60 sec | |
| DSN Radiometeric Tracking | S-Band Range | 1.0 m (1σ) : Every 10 min | |
| On-Board Optical[19] | Lunar Landmarks | 0.25 pixels (1σ) : 2/day | |

Figure 4 shows position and velocity error profiles over a nine-week simulation period. The DSN tracking frequency of three passes per week shows that the primary velocity requirement (<10 cm/sec, 3σ) can be met. Dynamical events such as perilune (red dashed vertical lines), wheel desaturations (light grey vertical dashed lines) and OMMs (blue vertical dashed lines) correlate with error increases as expected.

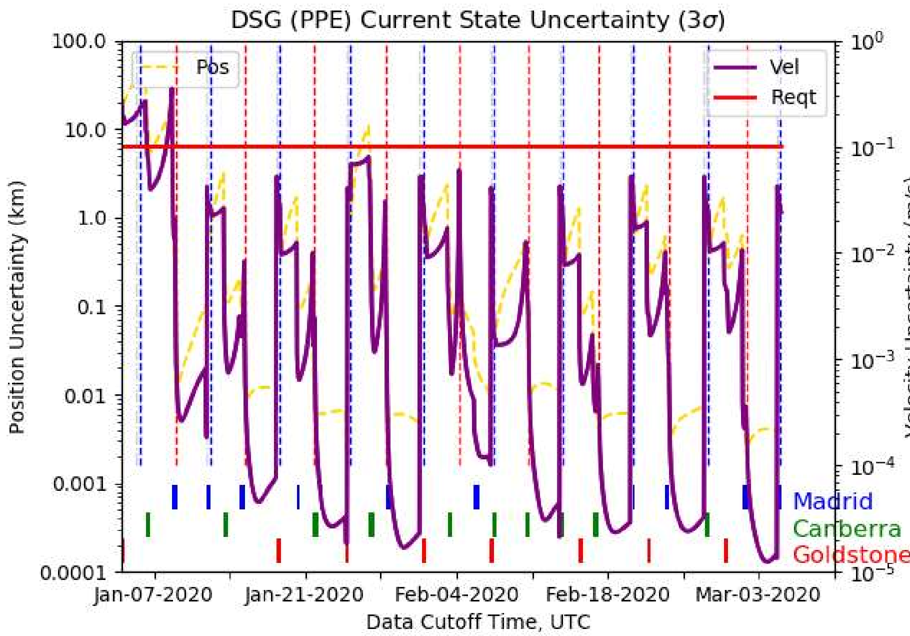



**Figure 4. DSN Tracking: 3 Passes/Week**

During crewed operations the PPE wheel desaturation frequency increases markedly from once every orbit to once every 140 minutes. In addition, venting from the Orion crew element, as documented in D'Souza and Barton*,* introduces orbit determination errors as shown in Figure 5. With near-continuous tracking during crewed operations, velocity uncertainties from these error sources remain below the established requirement.

Crew venting perturbations have the largest effect when the stack is least massive. The venting acceleration errors are directly proportional to the stack mass. For example, the $CO_2$ puff acceleration error in each axis for configuration 2 (42 t) is 4.4 x $10^{-7}$ m/s$^2$ (1σ). The acceleration uncertainties for the more massive stack of configuration 5 (80 t) is 2.3 x $10^{-7}$ m/s$^2$ (1σ).

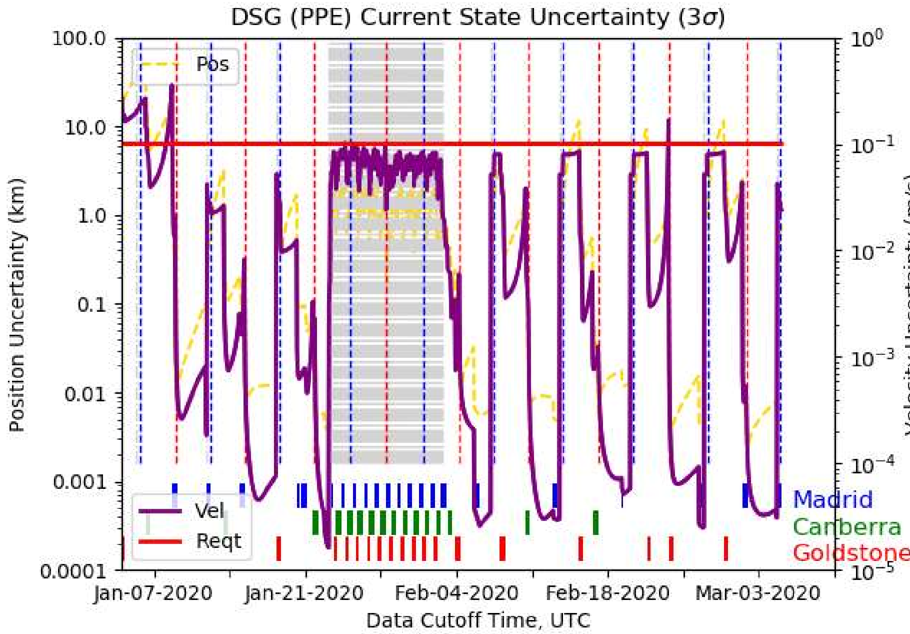
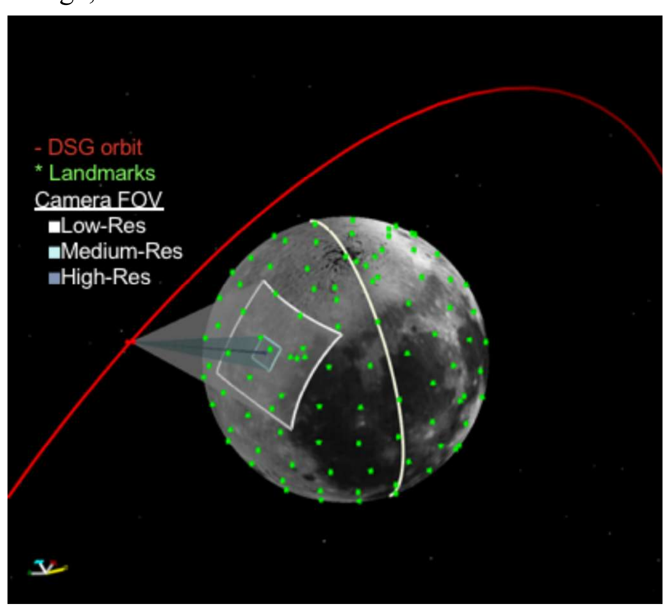



**Figure 5. DSN Tracking: Continuous During Crewed Operations**

Given the impact of wheel desaturation errors on the orbit determination, additional sensitivity analysis results were obtained. For uncrewed operations, three, six-hour DSN passes per week are adequate to maintain orbit determination knowledge with desaturation errors up to 2 cm/s (1σ). When crew elements are included, the tracking requirements increase to nearly continuous.

**On-Board Orbit Determination Performance**

The same ground-based simulation was extended using on-board optical observations. Figure 6 shows the global distribution of approximately 200 lunar landmarks. Error assumptions related to optical processing are included in Table 1. High, medium and low-resolution cameras were analyzed with implementation assumptions provided in Table 2. FOV is the camera field-of-view, **Θ** is the field-of-view of one camera pixel (typically known as the "instantaneous field-of-view" or IFOV). Nadir point, sunlit observations were assumed to be collected twice per day.




Figures 7-9 show position and velocity error profiles for the low, medium and high-resolution cameras. For all cases the velocity errors exceed the 10 cm/s (3σ) requirement around perilune. Since OMMs are planned to be designed and executed near apolune (within 2 days) these error excursions would not impact the ability to accurately design the OMMs.

**Figure 6. Optical Lunar Landmarks Globally Distributed**

**Table 2. Representative camera implementations.**

| Name | FOV (deg) | Θ (μrad) | Focal Length (mm) |
|---|---|---|---|
| Low-Res | 28 | 128 | 502 |
| Med-Res | 7 | 60 | 234 |
| High-Res | 0.6 | 10 | 2619 |

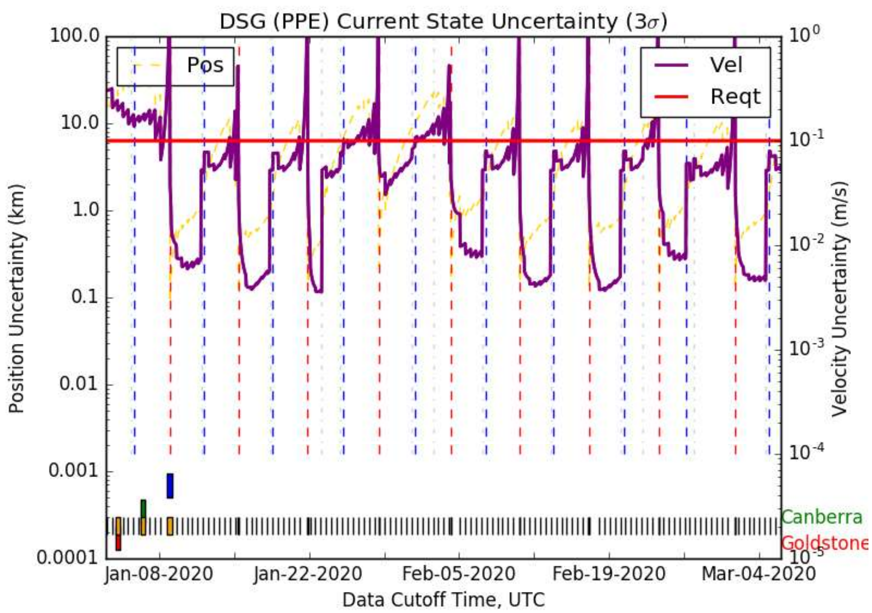



**Figure 7. On-Board Optical: Low-Resolution Camera**

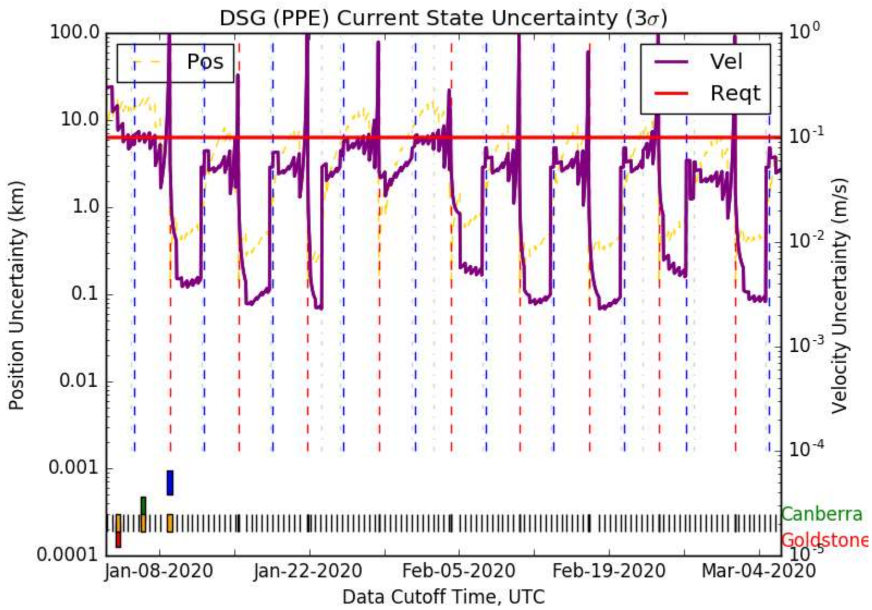



**Figure 8. On-Board Optical: Medium-Resolution Camera**

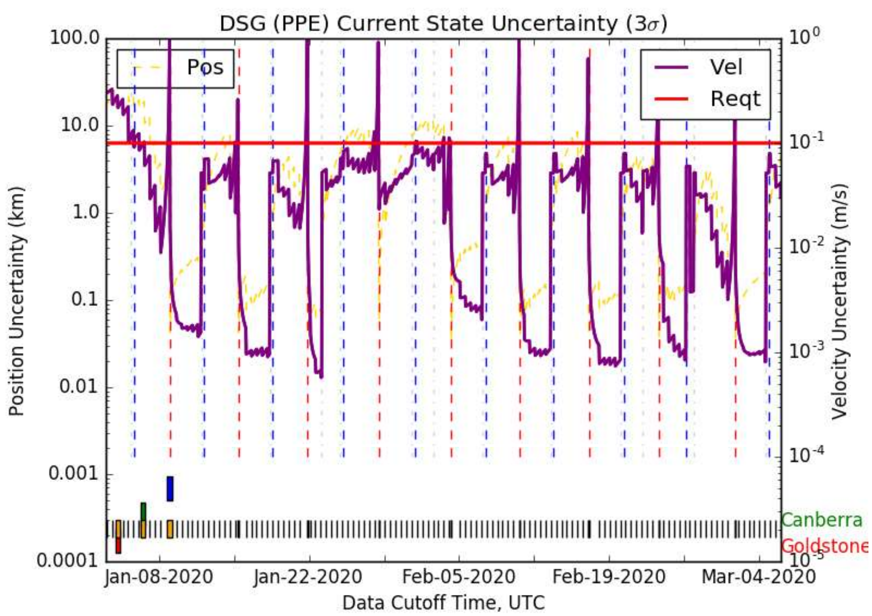



**Figure 9. On-Board Optical: High-Resolution Camera**

## CONCLUSIONS

An optical only version of DPS-Navigator, relying on lunar landmark tracking from the baseline NRHO Gateway orbit, can meet existing orbit knowledge requirements needed to design and execute orbit maintenance maneuvers. Thus, an alternative to traditional Earth-based radiometric techniques would be available to free Earth tracking stations and ground personnel for other support.

## ACKNOWLEDGMENTS

The authors would like to thank Ryan Whitley and Diane Davis for their programmatic and technical support to this task. The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. 

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